CORE
Metadata, citation and similar papers at core.ac.uk
Provided by Ghent University Academic Bibliography

CMS-SMP-17-006

CERN-EP-2017-177
2017/11/21

Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A measurement of vector boson scattering and constraints on anomalous quartic gauge couplings from events with two Z bosons and two jets are presented. The analysis is based on a data sample of proton–proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector and corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The search is performed in the fully leptonic final state $\mathrm{ZZ} \rightarrow \ell\ell\ell'\ell'$, where $\ell, \ell' = \mathrm{e}$ or μ. The electroweak production of two Z bosons in association with two jets is measured with an observed (expected) significance of 2.7 (1.6) standard deviations. A fiducial cross section for the electroweak production is measured to be $\sigma_{\mathrm{EW}}(\mathrm{pp} \rightarrow \mathrm{ZZjj} \rightarrow \ell\ell\ell'\ell'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$, which is consistent with the standard model prediction. Limits on anomalous quartic gauge couplings are determined in terms of the effective field theory operators T0, T1, T2, T8, and T9. This is the first measurement of vector boson scattering in the ZZ channel at the LHC.

Published in Physics Letters B as doi:10.1016/j.physletb.2017.10.020.

© 2017 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members

arXiv:1708.02812v2 [hep-ex] 17 Nov 2017

1 Introduction

Weak vector boson scattering (VBS) plays a central role in the standard model (SM) and is a key process to probe the non-Abelian gauge structure of the electroweak (EW) interaction. In the absence of any other contributions, the scattering amplitude of longitudinally polarized vector bosons would violate unitarity at center-of-mass energies for the scattering process of order 1 TeV [1, 2]. The discovery of a scalar boson at the CERN LHC [3, 4] with gauge couplings compatible with those predicted for the SM Higgs boson [5] provides evidence that contributions from the exchange of this boson may be responsible for preserving unitarity at high energies, as predicted in the SM.

Unitarity restoration for longitudinal boson scattering in the SM relies on the interference of the VBS amplitudes and amplitudes that involve the Higgs boson. Any deviation in the SM coupling of the Higgs boson to the gauge bosons breaks this delicate cancellation, thus permitting a test of the EW symmetry breaking mechanism (EWSB) of the SM. The study of differential cross sections for VBS processes at large diboson invariant masses provides a model-independent test of the Higgs boson couplings to vector bosons, complementing direct measurements of Higgs boson production and decay rates. Many models of physics beyond the SM alter the couplings of vector bosons, and the effects can be parametrized in an effective field theory approach [6]. The VBS topology increases the sensitivity to the contribution of the quartic interactions, allowing tests for the presence of anomalous quartic gauge couplings (aQGCs) [7].

At the LHC, VBS is initiated by quarks q from the colliding protons; both quarks radiate vector bosons (V = W, Z) which then interact. Because of the relatively small transverse momentum p_{T} carried by the gauge bosons and the absence of any color exchange at leading order (LO), VBS is characterized by the presence of two forward jets j in addition to the outgoing gauge bosons (qq $\to$ VVjj) and little hadronic activity between the two jets [8, 9]. The hard interaction in VBS only involves the EW interaction. Figure 1 shows some of the Feynman diagrams that contribute to the EW production of the VVjj signature, involving quartic (top left) and trilinear vertices (top right), as well as diagrams involving the Higgs boson (bottom left). The qq $\to$ VVjj process can also be mediated through the strong interaction (bottom right in Fig. 1), which leads to the same final state as the VBS signal, resulting in an irreducible background.

Both the ATLAS and CMS Collaborations performed searches for VBS using proton–proton collisions at $\sqrt{s} = 8$ TeV, notably in the same-sign WW channel [10–12]. The ATLAS Collaboration also reported limits on a fiducial cross section for VBS in the WZ channel [13]. The ZZ channel remained unprobed. Limits on aQGCs are reported in Refs. [10–18].

This paper presents the first experimental investigation of VBS in the ZZ channel and exploits the fully leptonic final state, where both Z bosons decay into electrons or muons, ZZ $\to \ell\ell\ell'\ell'$ (ℓ, $\ell' =$ e or μ). Despite a low cross section, a small Z $\to \ell\ell$ branching fraction, and a large irreducible QCD background, this channel provides a favorable laboratory to study EWSB because all final-state particles are reconstructed. The clean leptonic final state results in a small reducible background, where one or more of the reconstructed lepton candidates originate from the misidentification of jet fragments. This channel also provides a precise knowledge of the scattering energy. Furthermore, the spin correlations of the reconstructed fermions permit the extraction of the longitudinal contribution to VBS.

The search for the EW production of the $\ell\ell\ell'\ell'$jj final state is carried out using pp collisions at $\sqrt{s} = 13$ TeV recorded with the CMS detector at the LHC. The data set corresponds to an integrated luminosity of 35.9 fb^{-1} collected in 2016. A multivariate discriminant, which combines observables sensitive to the kinematics of the VBS process to separate the EW- from the

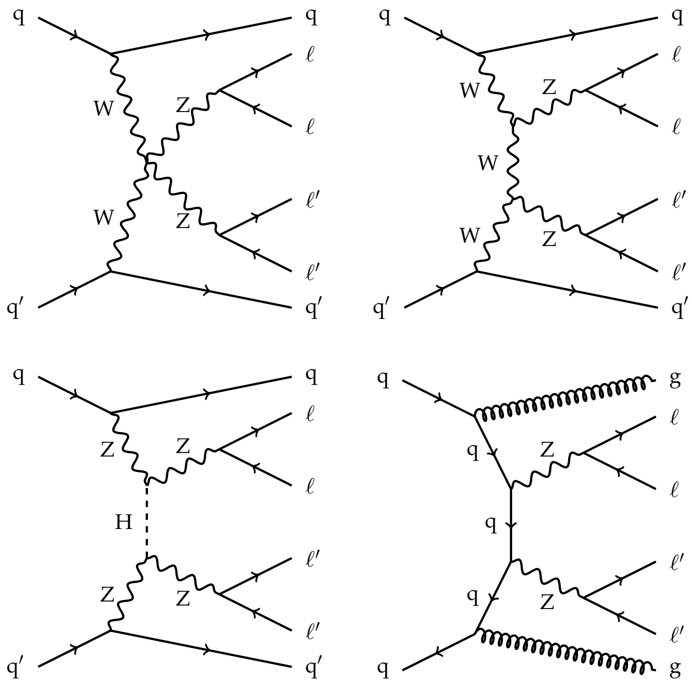

Figure 1: Representative Feynman diagrams for the EW- (top row and bottom left) and QCD-induced production (bottom right) of the ZZjj $\to \ell\ell\ell'\ell'$jj (ℓ, $\ell' =$ e or μ) final state. The scattering of massive gauge bosons as depicted in the top row is unitarized by the interference with amplitudes that feature the Higgs boson (bottom left).

QCD-induced production, is used to extract the signal significance and to measure the cross section for the EW production in a fiducial volume. Finally, the selected $\ell\ell\ell'\ell'$jj events are used to constrain aQGCs described by the operators T0, T1, and T2 as well as the neutral-current operators T8 and T9 [7].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are silicon pixel and strip tracking detectors, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity η coverage provided by the barrel and endcap detectors up to $|\eta| < 5$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles with $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [19].

Electrons are measured in the pseudorapidity range $|\eta| < 2.5$ using both the tracking system and the ECAL. The momentum resolution for electrons with $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$ from $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays ranges from 1.7% for nonshowering electrons in the barrel region ($|\eta| < 1.479$) to 4.5% for showering electrons in the endcaps [20].

Muons are measured in the pseudorapidity range $|\eta| < 2.4$ using the silicon tracker and muon systems. The muon detectors are constructed using three different technologies: drift tubes for $|\eta| < 1.2$, cathode strip chambers for $0.9 < |\eta| < 2.4$, and resistive plate chambers for $|\eta| < 1.6$. In the intermediate p_T range of $20 < p_T < 100$ GeV, matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1.3–2.0% in the barrel ($|\eta| < 1.2$), and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [21].

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from the nominal interaction point. For $|\eta| > 1.74$, the size of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the ECAL and HCAL calorimeters alone are used.

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest in a fixed time interval of 3.2 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage [22].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

3 Signal and background simulation

Several Monte Carlo event generators are used to simulate the signal and background contributions. The simulated samples are employed to optimize the event selection, to develop the multivariate discriminator, and to estimate the irreducible background yields.

The EW production of Z boson pairs and two final-state quarks, where the Z bosons decay leptonically, is simulated at LO using MADGRAPH5_aMC@NLO v2.3.3 (abbreviated as MG5_AMC in the following) [24]. The sample includes triboson processes, where the Z boson pair is accompanied by a third vector boson that decays into jets, as well as diagrams involving the quartic coupling vertex. The predictions from this sample are cross-checked with those obtained from the LO generator PHANTOM v1.2.8 [25], and excellent agreement in the yields and the multivariate distribution exploited for the signal extraction is found.

The event samples of the QCD-induced production of two Z bosons are simulated with zero, one, and two outgoing partons at Born level at next-to-leading order (NLO) with MG5_AMC. The different jet multiplicities are merged using the FxFx scheme [26] with a merging scale of 30 GeV, and leptonic Z boson decays are simulated using MADSPIN [27]. The interference between the EW and QCD diagrams is evaluated using dedicated samples produced with MG5_AMC at LO. It is found to contribute less than 1% to the total yield and is therefore neglected. The loop-induced production of two Z bosons, referred to as gg $\rightarrow$ ZZ, is simulated at LO with MCFM v.7.0.1 [28]. A dedicated MG5_AMC simulation of the loop-induced gg $\rightarrow$ ZZjj process is used to check the modeling of the ZZjj phase space in the MCFM sample, and good agreement is found.

Samples for $\mathrm{t\bar{t}Z}$ and WWZ production, background processes that contain four prompt, isolated leptons and additional jets in the final state, are simulated with MG5_AMC at NLO.

The simulation of the aQGC processes is performed at LO using MG5_AMC and employs matrix element reweighting to obtain a finely spaced grid in each of the five anomalous couplings probed by the analysis.

The PYTHIA v8.212 [29, 30] package is used for parton showering, hadronization, and the underlying event simulation, with parameters set by the CUETP8M1 tune [31]. The NNPDF3.0 [32] set of parton distribution functions (PDFs) is used, and the PDFs are calculated to the same order in QCD as the hard process. All simulated samples are normalized to the cross sections obtained from the respective event generator.

The detector response is simulated using a detailed description of the CMS detector implemented in the GEANT4 package [33, 34]. The simulated events are reconstructed using the same algorithms as used for the data. The simulated samples include additional interactions in the same and neighboring bunch crossings, referred to as pileup. Simulated events are weighted so that the pileup distribution reproduces that observed in the data, which has an average of about 23 interactions per bunch crossing.

4 Event selection

The final state should consist of at least two pairs of oppositely charged isolated leptons and at least two hadronic jets. The ZZ selection is similar to that used in the CMS inclusive ZZ cross section measurement [35].

The primary triggers require the presence of a pair of loosely isolated leptons. The highest p_{T} electron (muon) must have $p_{\mathrm{T}}^{\ell} > 23\,(17)\,\mathrm{GeV}$, and the next-to-highest p_{T} lepton must have $p_{\mathrm{T}}^{\ell} > 12\,(8)\,\mathrm{GeV}$. The dilepton triggers require that the tracks associated with the leptons originate from within 2 mm of each other along the beam axis. Triggers requiring a triplet of low-p_{T} leptons with no isolation criterion, as well as isolated single-electron and single-muon triggers with minimal p_{T} thresholds of 27 and 22 GeV, respectively, help to recover efficiency. The overall trigger efficiency for events that satisfy the ZZ selection described below is greater than 98%.

Events are reconstructed using a particle-flow algorithm [36] that reconstructs and identifies each individual particle with an optimized combination of all subdetector information. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particle-flow objects in an event. Its magnitude is referred to as $p_{\mathrm{T}}^{\text{miss}}$.

The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp interaction vertex. The physics objects are the objects returned by a jet finding algorithm [37, 38] applied to all charged tracks associated with the vertex, plus the corresponding associated $p_{\mathrm{T}}^{\text{miss}}$. Leptons and jets are required to originate from the primary vertex.

Electrons are identified using a multivariate classifier, which includes observables sensitive to bremsstrahlung along the electron trajectory, the geometrical and energy-momentum compatibility between the electron track and the associated energy cluster in the ECAL, the shape of the electromagnetic shower, and variables that discriminate against electrons originating from photon conversions [20].

Muons are reconstructed by combining information from the silicon tracker and the muon system [21]. The matching between the inner and outer tracks proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track in the silicon tracker.

The muons are selected from the reconstructed muon track candidates by applying minimal requirements on the track in both the muon system and silicon tracker, and taking into account compatibility with small energy deposits in the calorimeters.

In order to suppress electrons from photon conversions and muons originating from in-flight decays of hadrons, we require the three-dimensional impact parameter of each lepton track, computed with respect to the primary vertex position, to be less than four times the uncertainty on the impact parameter.

Leptons are required to be isolated from other particles in the event. The relative isolation is defined as

$$R_{\mathrm{iso}} = \Big[\sum_{\substack{\text{charged}\\ \text{hadrons}}} p_{\mathrm{T}} + \max\big(0, \sum_{\substack{\text{neutral}\\ \text{hadrons}}} p_{\mathrm{T}} + \sum_{\text{photons}} p_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{PU}}\big) \Big] \Big/ p_{\mathrm{T}}^{\ell}, \tag{1}$$

where the sums run over the charged and neutral hadrons and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton trajectory. To minimize the contribution of charged particles from pileup to the isolation calculation, charged hadrons are included only if they originate from the primary vertex. The contribution of neutral particles from pileup is $p_{\mathrm{T}}^{\mathrm{PU}}$. For electrons, $p_{\mathrm{T}}^{\mathrm{PU}}$ is evaluated with the jet area method described in Ref. [39]. For muons, $p_{\mathrm{T}}^{\mathrm{PU}}$ is taken to be half the p_{T} sum of all charged particles in the cone originating from pileup vertices. The factor of one-half accounts for the expected ratio of charged to neutral particle energy in hadronic interactions. Leptons with $R_{\mathrm{iso}} < 0.35$ are considered isolated.

The efficiency of the lepton reconstruction and selection is measured in bins of p_{T}^{ℓ} and η^{ℓ} using the tag-and-probe technique. The measured efficiencies are used to correct the simulation. The lepton momentum scales are calibrated in bins of p_{T}^{ℓ} and η^{ℓ} using the decay products of known dilepton resonances. The electron momentum scale for data is corrected with a $\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}$ sample by matching the peak of the reconstructed dielectron mass spectrum to the known value of m_{Z}. A Gaussian smearing of the electron energies in the simulation is also applied to match the $\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}$ mass resolution in data. Muon momenta are calibrated using a Kalman filter approach [40], using J/ψ meson and Z boson decays.

An algorithm is used to identify final-state radiation (FSR) from the leptons [41]. A photon with $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ and within a cone of $\Delta R = 0.5$ around the lepton momentum direction is selected if it satisfies quality requirements. The FSR photons identified by the algorithm are excluded from the lepton isolation computation.

Jets are reconstructed from particle-flow candidates using the anti-k_{T} clustering algorithm [37], as implemented in the FASTJET package [38], with a distance parameter of 0.4. In order to assure a good reconstruction efficiency and to reduce the instrumental background as well as the contamination from pileup, loose identification criteria based on the multiplicities and energy fractions carried by charged and neutral hadrons are imposed on jets [42]. Only jets with $|\eta| < 4.7$ are considered.

Jet energy corrections are extracted from data and simulated events to account for the effects of pileup, uniformity of the detector response, and residual differences between the jet energy scale in the data and in the simulation. The jet energy scale calibration [43–45] relies on corrections parameterized in terms of the uncorrected p_{T} and η of the jet, and is applied as a multiplicative factor, scaling the four-momentum vector of each jet. In order to ensure that jets are well measured and to reduce the pileup contamination, all jets must have a corrected p_{T} larger than 30 GeV.

A signal event must contain at least two Z candidates, each formed from pairs of isolated electrons or muons of opposite charges. Only reconstructed electrons (muons) with a $p_T > 7\ (5)\,\text{GeV}$ are considered. Among the four leptons, the highest p_T lepton must have $p_T > 20\,\text{GeV}$, and the second-highest p_T lepton must have $p_T > 12\ (10)\,\text{GeV}$ if it is an electron (muon). All leptons are required to be separated by $\Delta R\,(\ell_1, \ell_2) > 0.02$, and electrons are required to be separated from muons by $\Delta R\,(\text{e}, \mu) > 0.05$.

Within each event, all permutations of leptons giving a valid pair of Z candidates are considered. For each ZZ candidate, the lepton pair with the invariant mass closest to the nominal Z boson mass is denoted Z_1 and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2. Both m_{Z_1} and m_{Z_2} are required to be less than 120 GeV. All pairs of oppositely charged leptons, regardless of flavor, in the ZZ candidate are required to satisfy $m_{\ell\ell'} > 4\,\text{GeV}$ to suppress backgrounds from hadron decays.

If multiple ZZ candidates in an event pass this selection, the candidate with m_{Z_1} closest to the nominal Z boson mass is chosen. In the rare case (0.3%) of further ambiguity, which may arise in events with more than four leptons, the Z_2 candidate that maximizes the scalar p_T sum of the four leptons is chosen. Finally, the Z_1 and Z_2 candidates must have masses between 60 and 120 GeV. This selection is referred to as the ZZ selection.

The search for the EW production of two Z bosons is performed on a subset of events that pass the ZZ selection, namely those that feature at least two jets. The jets are required to be separated from the leptons of the ZZ candidate by $\Delta R = 0.4$. The two highest p_T jets are referred to as the tagging jets and their invariant mass is required to be larger than 100 GeV. This selection is referred to as the ZZjj selection.

5 Background estimation

The dominant background is the QCD-induced production of two Z bosons in association with jets, as shown in the bottom right diagram of Fig. 1. The yield and shape of the multivariate discriminant of this irreducible background are taken from simulation, but ultimately constrained by the data in the fit that extracts the EW signal, as described in Section 7. Other irreducible backgrounds arise from processes that produce four genuine high-p_T isolated leptons, $\text{pp} \to \text{t}\bar{\text{t}}\text{Z} + \text{jets}$ and $\text{pp} \to \text{WWZ} + \text{jets}$. These small contributions feature kinematic distributions similar to that of the dominant background and are estimated using simulation.

Reducible backgrounds arise from processes in which heavy-flavor jets produce secondary leptons or from processes in which jets are misidentified as leptons. The lepton identification and isolation requirements significantly suppress this background, which is very small compared to the signal after the selection.

The reducible background, referred to as Z + X, is predominately composed of Z + jets events, with minor contributions from $\text{t}\bar{\text{t}}$ + jets and WZ + jets processes. This reducible contribution is estimated from data by inverting the lepton selection criteria and weighting events in control regions using a lepton misidentification rate which is also determined from data. Two control regions serve to estimate the reducible background from events with one or two misidentified leptons, respectively.

Events in the control region with one (two) misidentified lepton(s) satisfy the ZZjj selection, with the exception that one of the Z boson candidates is constructed from one (two) lepton(s) that fail the identification or isolation criteria. The lepton misidentification rate is measured by selecting events that feature one Z boson candidate and a third reconstructed lepton. The fraction of events for which the third lepton satisfies the identification and isolation criteria is taken as the lepton misidentification rate. The procedure is identical to that used in Ref. [35] and is described in more detail in Ref. [41].

6 Systematic uncertainties

Several sources of systematic uncertainty are considered and evaluated by varying each relevant parameter. The resulting changes to the distribution of the multivariate discriminant, both in shape and yield, are taken into account. The impact of the variation for each source of uncertainty is summarized below.

Renormalization and factorization scale uncertainties are evaluated by varying both scales independently by factors of two and one-half, removing combinations where both variations differ by a factor of four, and amount to 10 (7)% for the dominant QCD background (EW signal). The PDF + α_s variations are evaluated following the PDF4LHC prescription [46], and increase from 6% at low values of the multivariate discriminant to 9% in the signal-rich region. A 40% uncertainty in the yield of the loop-induced ZZjj background is assigned. The impact of the jet energy scale uncertainty amounts to 20 (4)% at low (high) values of the multivariate discriminant and the impact of the jet energy resolution uncertainty is 8% [44, 45]. The uncertainties in the QCD background normalization and the jet energy scale are the dominant systematic uncertainties in the measurement. Higher order EW corrections in VBS processes are known to be negative and at the level of tens of percent [47], but such corrections have not been calculated for the final state considered in this paper, and therefore are not considered here. Nevertheless, the impact of such NLO EW corrections would be negligible in this analysis, which is limited by the large statistical uncertainty. The uncertainty in the lepton reconstruction and selection efficiency is 6/4/2% in the 4e/2e2μ/4μ final states, respectively. The uncertainty in the integrated luminosity is 2.5% [48]. The systematic uncertainty in the trigger efficiencies is evaluated by taking the difference between the trigger efficiencies measured in data and in simulated events, and amounts to 2%. A 40% yield uncertainty in the reducible background estimate based on data samples takes into account the limited number of events in the control regions as well as the mismatch in the background composition in the control regions used to determine the lepton misidentification rates and the control regions used to estimate the yield in the signal region.

7 Search for EW ZZjj production

The expected signal purity in the ZZjj selection is about 5%, with 83% of events coming from QCD-induced production. Additional kinematic selections are therefore necessary to enhance the contribution from EW production. Figure 2 shows the absolute dijet pseudorapidity separation $|\Delta\eta_{jj}|$ and the dijet invariant mass m_{jj} for events passing the ZZjj selection. Table 1 shows the expected and observed number of events for the ZZjj selection and illustrates the increase of the VBS signal purity obtained with an exemplary selection that requires $m_{jj} > 400\,\mathrm{GeV}$ and $|\Delta\eta_{jj}| > 2.4$.

Table 1: Signal and background yields for the ZZjj selection and for an illustrative VBS signal-enriched selection that requires $m_{jj} > 400\,\mathrm{GeV}$ and $|\Delta\eta_{jj}| > 2.4$.

Selection	$t\bar{t}Z$ and WWZ	QCD ZZjj	Z + X	Total bkg.	EW ZZjj	Total expected	Data
ZZjj	7.1 ± 0.8	97 ± 14	6.6 ± 2.5	111 ± 14	6.2 ± 0.7	117 ± 14	99
VBS signal-enriched	0.9 ± 0.2	19 ± 4	0.7 ± 0.3	20 ± 4	4 ± 0.5	25 ± 4	19

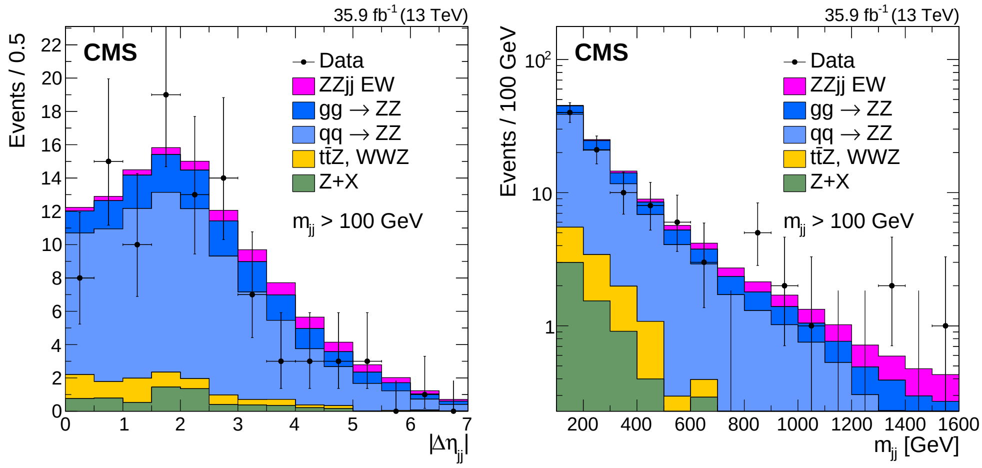

Figure 2: Distribution of the dijet pseudorapidity separation (left) and dijet invariant mass (right) for events passing the ZZjj selection, which requires $m_{\mathrm{jj}} > 100\,\mathrm{GeV}$. Points represent the data, filled histograms the expected signal and background contributions. No data beyond $|\Delta\eta_{\mathrm{jj}}| > 7$ (left) and $m_{\mathrm{jj}} > 1600\,\mathrm{GeV}$ (right) is observed.

The determination of the signal strength for the EW production, i.e., the ratio of the measured cross section to the SM expectation $\mu = \sigma/\sigma_{\mathrm{SM}}$, employs a multivariate discriminant to optimally separate the signal and the QCD background. The scikit-learn framework [49] is used to train and optimize a boosted decision tree (BDT) on simulated events to exploit the kinematic differences between the EW signal and the QCD background. Seven observables are used in the BDT, including m_{jj}, $|\Delta\eta_{\mathrm{jj}}|$, m_{ZZ}, as well as the Zeppenfeld variables [8] $\eta^*_{\mathrm{Z}_i} = \eta_{\mathrm{Z}_i} - (\eta_{\mathrm{jet\,1}} + \eta_{\mathrm{jet\,2}})/2$ of the two Z bosons, and the ratio between the p_{T} of the tagging jet system and the scalar p_{T} sum of the tagging jets. The BDT also exploits the event balance $Rp_{\mathrm{T}}^{\mathrm{hard}}$, which is defined as the transverse component of the vector sum of the Z bosons and tagging jets momenta, normalized to the scalar p_{T} sum of the same objects [50].

A total of 36 discriminating variables including observables sensitive to parton emissions between the tagging jets, the production and decay angles of the leptons, Z bosons, and tagging jets as well as quark-gluon tagging information are considered in the BDT training. Observables that do not improve the area under the signal-versus-background efficiency curve (AUC) are removed from the BDT. The observables sensitive to extra parton emissions provide little marginal AUC increase and are not retained because of the limited modelling accuracy in the simulation. The tunable hyper-parameters of the BDT training algorithm are optimized via a grid-search algorithm. Finally, the BDT performance is checked using a matrix element approach [51–53] that provides a similar separation between the signal and background processes.

To validate the modeling of the backgrounds in the search, a QCD-enriched control region is defined by selecting events with $m_{\mathrm{jj}} < 400\,\mathrm{GeV}$ or $|\Delta\eta_{\mathrm{jj}}| < 2.4$. Good agreement is observed between the data and SM expectation in this control region, as shown in Fig. 3 (left). The classifier output distribution for all events in the ZZjj selection including the high signal purity contribution at large BDT output values is shown in Fig. 3 (right).

The BDT distribution of the events in the ZZjj selection is used to extract the significance of the EW signal via a maximum-likelihood fit. The expected distributions for the signal and the irreducible backgrounds are taken from the simulation while the reducible background is estimated from the data. The shape and normalization of each distribution are allowed to vary in the fit within the respective uncertainties. This approach constrains the yield of the QCD-

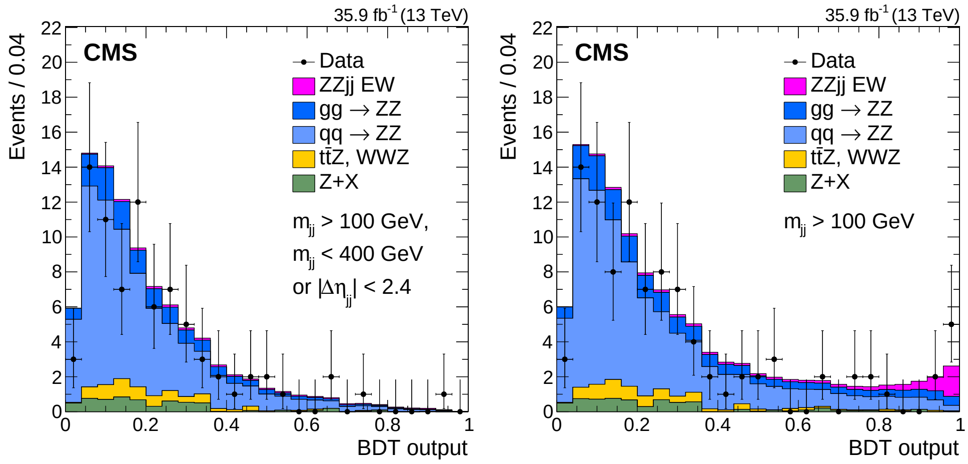

Figure 3: Distribution of the BDT output in the control region obtained by selecting ZZjj events with $m_{\mathrm{jj}} < 400\,\mathrm{GeV}$ or $|\Delta\eta_{\mathrm{jj}}| < 2.4$ (left) and for the ZZjj selection (right). Points represent the data, filled histograms the expected signal and background contributions.

induced production from the background-enriched region of the BDT distribution.

The systematic uncertainties are treated as nuisance parameters in the fit and profiled [54]. The post-fit values are then used to extract the signal strength. The signal strength is measured to be $\mu = 1.39^{+0.72}_{-0.57}\,(\mathrm{stat})\,^{+0.46}_{-0.31}\,(\mathrm{syst}) = 1.39^{+0.86}_{-0.65}$ and the background-only hypothesis is excluded with a significance of 2.7 standard deviations (1.6 standard deviations expected).

The measured signal strength is used to determine the fiducial cross section for the EW production. The fiducial volume is almost identical to the selections imposed at the reconstruction level, the only difference being the lepton thresholds of $p_{\mathrm{T}}^{\ell} > 5\,\mathrm{GeV}$ and $|\eta|^{\ell} < 2.5$. The generator-level lepton momenta are corrected by adding the momenta of generator-level photons within $\Delta R(\ell,\gamma) < 0.1$. The kinematic selection of the Z bosons and the final ZZjj candidate proceeds as the reconstruction-level selection. The observed signal strength corresponds to a fiducial cross section of $\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{ZZjj} \to \ell\ell\ell'\ell'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$, compatible with the SM prediction of $0.29^{+0.02}_{-0.03}\,\mathrm{fb}$.

8 Limits on anomalous quartic gauge couplings

The events in the ZZjj selection are used to constrain aQGCs in the effective field theory approach. The ZZjj channel is sensitive to the operators T0, T1, and T2, as well as the neutral current operators T8 and T9 [7]. The former operators are constructed from the $\mathrm{SU}_L(2)$ gauge fields, while the latter only involve the $\mathrm{U}_Y(1)$ fields. As a consequence, the T8 and T9 operators are experimentally accessible only via final states involving the neutral gauge bosons. The effect of a nonzero aQGC is to enhance the production cross section at large masses of the ZZ system. Thus the m_{ZZ} distribution is used to constrain the aQGC parameters $f_{\mathrm{T}i}/\Lambda^4$. The increase of the yield exhibits a quadratic dependence on the anomalous coupling, and a parabolic function is fitted to the per-mass bin yields, allowing for an interpolation between the discrete coupling parameters of the simulated signals. The statistical analysis employs the same methodology used for the signal strength, including the profiling of the systematic uncertainties. The distributions of the background model, including the EW component, are normalized to their respective SM predictions. The Wald Gaussian approximation and Wilks' theorem are used to derive 95% confidence level (CL) limits on the aQGC parameters [55–57]. The measurement is statistically limited.

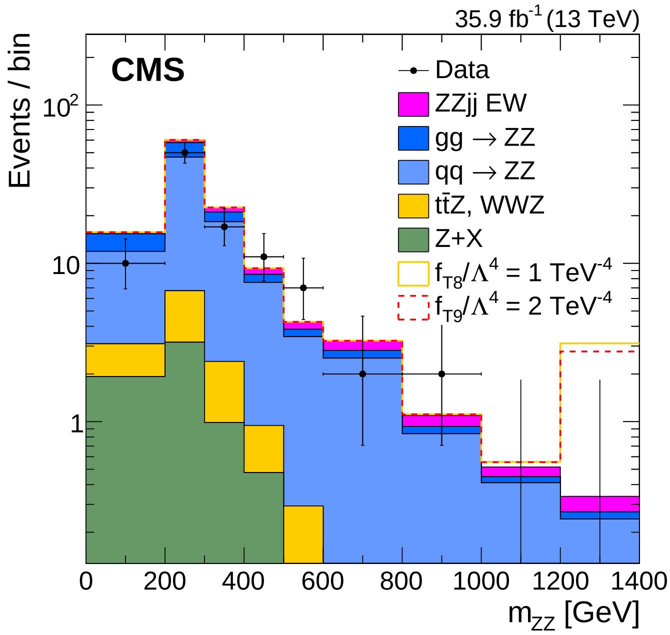

Figure 4: The m_{ZZ} distribution in the ZZjj selection together with the SM prediction and two hypotheses for the aQGC coupling strengths. Points represent the data, filled histograms the expected signal and background contributions. The last bin includes all contributions with $m_{ZZ} > 1200\,\mathrm{GeV}$.

Table 2: Expected and observed lower and upper 95% CL limits on the couplings of the quartic operators T0, T1, and T2, as well as the neutral current operators T8 and T9. The unitarity bounds are also listed. All coupling parameter limits are in TeV^{-4}, while the unitarity bounds are in TeV.

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.53	0.51	-0.46	0.44	2.5
f_{T1}/Λ^4	-0.72	0.71	-0.61	0.61	2.3
f_{T2}/Λ^4	-1.4	1.4	-1.2	1.2	2.4
f_{T8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

Figure 4 shows the expected m_{ZZ} distribution for the SM and two aQGC scenarios. Table 2 lists the individual lower and upper limits obtained by setting all other anomalous couplings to zero, as well as the unitarity bound. The unitarity bound is determined using the VBFNLO framework [58] as the scattering energy m_{ZZ} at which the aQGC coupling strength set equal to the observed limit would result in a scattering amplitude that violates unitarity. These are the most stringent limits to date on the aQGC parameters $f_{T0,1,2}/\Lambda^4$ and $f_{T8,9}/\Lambda^4$.

9 Summary

A search was performed for vector boson scattering in the four-lepton and two-jet final state using proton–proton collisions at 13 TeV. The data correspond to an integrated luminosity of 35.9 fb^{-1} collected with the CMS detector at the LHC.

The electroweak production of two Z bosons in association with two jets was measured with an observed (expected) significance of 2.7 (1.6) standard deviations. The fiducial cross section is $\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{ZZjj} \to \ell\ell\ell'\ell'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$, consistent with the standard model prediction of $0.29^{+0.02}_{-0.03}$ fb.

Limits on anomalous quartic gauge couplings were set at the 95% confidence level in terms of effective field theory operators, in units of TeV^{-4}:

$$\begin{aligned}
-0.46 < f_{\mathrm{T0}}/\Lambda^4 < 0.44 \\
-0.61 < f_{\mathrm{T1}}/\Lambda^4 < 0.61 \\
-1.2 < f_{\mathrm{T2}}/\Lambda^4 < 1.2 \\
-0.84 < f_{\mathrm{T8}}/\Lambda^4 < 0.84 \\
-1.8 < f_{\mathrm{T9}}/\Lambda^4 < 1.8 \ .
\end{aligned}$$

These are the first results for the electroweak production of two Z bosons in association with jets at the LHC and the most stringent limits on the T0, T1, T2, T8, and T9 anomalous quartic gauge couplings to date.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References

[1] B. W. Lee, C. Quigg, and H. B. Thacker, "Strength of Weak Interactions at Very High Energies and the Higgs Boson Mass", *Phys. Rev. Lett.* **38** (1977) 883, `doi:10.1103/PhysRevLett.38.883`.

[2] B. W. Lee, C. Quigg, and H. B. Thacker, "Weak interactions at very high energies: The role of the Higgs boson mass", *Phys. Rev. D* **16** (1977) 1519, `doi:10.1103/PhysRevD.16.1519`.

[3] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, `doi:10.1016/j.physletb.2012.08.020`, `arXiv:1207.7214`.

[4] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, `doi:10.1016/j.physletb.2012.08.021`, `arXiv:1207.7235`.

[5] ATLAS and CMS Collaborations, "Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **08** (2016) 045, `doi:10.1007/JHEP08(2016)045`, `arXiv:1606.02266`.

[6] C. Degrande et al., "Effective field theory: A modern approach to anomalous couplings", *Annals Phys.* **335** (2013) 21, `doi:10.1016/j.aop.2013.04.016`, `arXiv:1205.4231`.

[7] O. J. P. Éboli, M. C. Gonzalez-Garcia, and J. K. Mizukoshi, "$pp \to jj e^{\pm}\mu^{\pm}\nu\nu$ and $jj e^{\pm}\mu^{\mp}\nu\nu$ at $\mathcal{O}(\alpha_{\mathrm{em}}^6)$ and $\mathcal{O}(\alpha_{\mathrm{em}}^4\alpha_{\mathrm{s}}^2)$ for the study of the quartic electroweak gauge boson vertex at CERN LHC", *Phys. Rev. D* **74** (2006) 073005, `doi:10.1103/PhysRevD.74.073005`, `arXiv:hep-ph/0606118`.

[8] D. Rainwater, R. Szalapski, and D. Zeppenfeld, "Probing color singlet exchange in Z+2-jet events at the CERN LHC", *Phys. Rev. D* **54** (1996) 6680, `doi:10.1103/PhysRevD.54.6680`, `arXiv:hep-ph/9605444`.

[9] V. A. Khoze, M. G. Ryskin, W. J. Stirling, and P. H. Williams, "A Z-monitor to calibrate Higgs production via vector boson fusion with rapidity gaps at the LHC", *Eur. Phys. J. C* **26** (2003) 429, `doi:10.1140/epjc/s2002-01069-2`, `arXiv:hep-ph/0207365`.

[10] ATLAS Collaboration, "Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector", *Phys. Rev. Lett.* **113** (2014) 141803, doi:10.1103/PhysRevLett.113.141803, arXiv:1405.6241.

[11] CMS Collaboration, "Study of Vector Boson Scattering and Search for New Physics in Events with Two Same-Sign Leptons and Two Jets", *Phys. Rev. Lett.* **114** (2015) 051801, doi:10.1103/PhysRevLett.114.051801, arXiv:1410.6315.

[12] ATLAS Collaboration, "Measurement of $W^{\pm}W^{\pm}$ vector-boson scattering and limits on anomalous quartic gauge couplings with the ATLAS detector", *Phys. Rev.* **D96** (2017), no. 1, 012007, doi:10.1103/PhysRevD.96.012007, arXiv:1611.02428.

[13] ATLAS Collaboration, "Measurements of $W^{\pm}Z$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector and limits on anomalous gauge boson self-couplings", *Phys. Rev. D* **93** (2016) 092004, doi:10.1103/PhysRevD.93.092004, arXiv:1603.02151.

[14] CMS Collaboration, "Evidence for exclusive $\gamma\gamma \to \mathrm{W}^+\mathrm{W}^-$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **08** (2016) 119, doi:10.1007/JHEP08(2016)119, arXiv:1604.04464.

[15] ATLAS Collaboration, "Search for anomalous electroweak production of WW/WZ in association with a high-mass dijet system in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *Phys. Rev. D* **95** (2017) 032001, doi:10.1103/PhysRevD.95.032001, arXiv:1609.05122.

[16] CMS Collaboration, "Measurement of the cross section for electroweak production of $\mathrm{Z}\gamma$ in association with two jets and constraints on anomalous quartic gauge couplings in proton–proton collisions at $\sqrt{s} = 8$ TeV", *Phys. Lett. B* **770** (2017) 380, doi:10.1016/j.physletb.2017.04.071, arXiv:1702.03025.

[17] CMS Collaboration, "Measurement of electroweak-induced production of $\mathrm{W}\gamma$ with two jets in pp collisions at $\sqrt{s} = 8$ TeV and constraints on anomalous quartic gauge couplings", *JHEP* **06** (2017) 106, doi:10.1007/JHEP06(2017)106, arXiv:1612.09256.

[18] ATLAS Collaboration, "Studies of $Z\gamma$ production in association with a high-mass dijet system in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *JHEP* **07** (2017) 107, doi:10.1007/JHEP07(2017)107, arXiv:1705.01966.

[19] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[20] CMS Collaboration, "Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV", *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[21] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[22] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[23] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[24] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[25] A. Ballestrero et al., "PHANTOM: A Monte Carlo event generator for six parton final states at high energy colliders", *Comput. Phys. Commun.* **180** (2009) 401, doi:10.1016/j.cpc.2008.10.005, arXiv:0801.3359.

[26] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO", *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.

[27] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, "Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations", *JHEP* **03** (2013) 015, doi:10.1007/JHEP03(2013)015, arXiv:1212.3460.

[28] J. M. Campbell and R. K. Ellis, "MCFM for the Tevatron and the LHC", *Nucl. Phys. B Proc. Suppl.* **205-206** (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.

[29] T. Sjöstrand, S. Mrenna, and P. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[30] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[31] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[32] NNPDF Collaboration, "Parton distributions for the LHC run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[33] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[34] J. Allison et al., "GEANT4 developments and applications", *IEEE Trans. Nucl. Sci.* **53** (2006) 270, doi:10.1109/TNS.2006.869826.

[35] CMS Collaboration, "Measurement of the ZZ production cross section and $\mathrm{Z} \to \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$", *Phys. Lett. B* **763** (2016) 280, doi:10.1016/j.physletb.2016.10.054, arXiv:1607.08834.

[36] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[37] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[38] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[39] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

[40] Frühwirth, R., "Application of Kalman filtering to track and vertex fitting", *Nucl. Instrum. Meth. A* **262** (1987) 444, doi:10.1016/0168-9002(87)90887-4.

[41] CMS Collaboration, "Measurement of the properties of a Higgs boson in the four-lepton final state", *Phys. Rev. D* **89** (2014) 092007, doi:10.1103/PhysRevD.89.092007, arXiv:1312.5353.

[42] CMS Collaboration, "Jet algorithms performance in 13 TeV data", CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.

[43] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[44] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[45] CMS Collaboration, "Jet energy scale and resolution performances with 13 TeV data", CMS Detector Performance Summary CMS-DP-2016-020, 2016.

[46] J. Butterworth et al., "PDF4LHC recommendations for LHC Run II", *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[47] B. Biedermann, A. Denner, and M. Pellen, "Large Electroweak Corrections to Vector-Boson Scattering at the Large Hadron Collider", *Phys. Rev. Lett.* **118** (2017) 261801, doi:10.1103/PhysRevLett.118.261801, arXiv:1611.02951.

[48] CMS Collaboration, "CMS luminosity measurements for the 2016 data taking period", CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

[49] F. Pedregosa et al., "Scikit-learn: Machine Learning in Python", *J. Machine Learning Res.* **12** (2011) 2825, arXiv:1201.0490.

[50] CMS Collaboration, "Measurement of electroweak production of two jets in association with a Z boson in proton–proton collisions at $\sqrt{s} = 8\,\text{TeV}$", *Eur. Phys. J. C* **75** (2015) 66, doi:10.1140/epjc/s10052-014-3232-5, arXiv:1410.3153.

[51] Y. Gao et al., "Spin determination of single-produced resonances at hadron colliders", *Phys. Rev. D* **81** (2010) 075022, doi:10.1103/PhysRevD.81.075022, arXiv:1001.3396. [Erratum: *Phys. Rev. D* **81** (2010) 079905 doi:10.1103/PhysRevD.81.079905].

[52] S. Bolognesi et al., "Spin and parity of a single-produced resonance at the LHC", *Phys. Rev. D* **86** (2012) 095031, doi:10.1103/PhysRevD.86.095031, arXiv:1208.4018.

[53] I. Anderson et al., "Constraining anomalous HVV interactions at proton and lepton colliders", *Phys. Rev. D* **89** (2014) 035007, doi:10.1103/PhysRevD.89.035007, arXiv:1309.4819.

[54] ATLAS and CMS Collaborations, LHC Higgs Combination Group, "Procedure for the LHC higgs boson search combination in Summer 2011", CMS-NOTE-2011-005; ATL-PHYS-PUB-2011-11, 2011.

[55] A. L. Read, "Presentation of search results: the CL_s technique", *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[56] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[57] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[58] K. Arnold et al., "VBFNLO: A parton level Monte Carlo for processes with electroweak bosons", *Comput. Phys. Commun.* **180** (2009) 1661, doi:10.1016/j.cpc.2009.03.006, arXiv:0811.4559.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler[1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, D. Rabady, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang[2]

Ghent University, Ghent, Belgium
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium
N. Beliy

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], A. Custódio, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, S. Stoykova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[5], X. Gao[5]

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger[7], M. Finger Jr.[7]

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[8,9], S. Elgammal[9], A. Mahrous[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram[11], J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[11], X. Coubez, J.-C. Fontaine[11], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[12], V. Sordini, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[7]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[7]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[13]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[14], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn,

E. Eren, E. Gallo[15], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[16], H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[16], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo[13], T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann[13], S.M. Heindl, U. Husemann, F. Kassel[13], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, G. Pasztor, G.I. Veres[17]

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[18], Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi[17], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[19], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
M. Bartók[17], P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India
S. Bahinipati[20], S. Bhowmik, P. Mal, K. Mandal, A. Nayak[21], D.K. Sahoo[20], N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, N. Dhingra, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, Aashaq Shah, A. Bhardwaj, S. Chauhan, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[13], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[22], G. Majumder, K. Mazumdar, T. Sarkar[22], N. Wickramage[23]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[24], E. Eskandari Tadavani, S.M. Etesami[24], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[25], F. Rezaei Hosseinabadi, B. Safarzadeh[26], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,13], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,27], G. Sguazzoni[a], D. Strom[a], L. Viliani[a,b,13]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[13]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], L. Brianza[a,b], F. Brivio[a,b], V. Ciriolo[a,b], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], K. Pauwels[a,b], D. Pedrini[a], S. Pigazzini[a,b,28], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,13], F. Fabozzi[a,c], F. Fienga[a,b], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,13], P. Paolucci[a,13], C. Sciacca[a,b], F. Thyssen[a]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a,13], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], E. Torassa[a], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti, C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a,13], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a,27], F. Ligabue[a,c], T. Lomtadze[a], E. Manca[a,c], G. Mandorli[a,c], L. Martini[a,b], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A. Savoy-Navarro[a,29], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], N. Daci[a], D. Del Re[a,b,13], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], F. Margaroli[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], R. Gomez Ambrosio, B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b],

E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], F. Ravera[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], A. Staiano[a], P. Traczyk[a,b]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonbuk National University, Jeonju, Korea
A. Lee

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[30], F. Mohamad Idris[31], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[32], Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[33], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[34,35], V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim[36], E. Kuznetsova[37], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin[35]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[38], M. Danilov[38], P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[35], I. Dremin[35], M. Kirakosyan[35], A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[39], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[40], Y.Skovpen[40], D. Shtol[40]

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[41], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares, A. Álvarez Fernández

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, E. Curras, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban[16], J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer[13], M.J. Kortelainen, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[42], F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[43], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[44], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[45], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl[†], L. Caminada[46], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijnsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi,

J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[47], M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Cerci[48], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[49], E.E. Kangal[50], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut[51], K. Ozdemir[52], D. Sunar Cerci[48], B. Tali[48], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, G. Karapinar[53], K. Ocalan[54], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya[55], O. Kaya[56], S. Tekten, E.A. Yetkin[57]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold[58], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[59], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko[6], V. Palladino, M. Pesaresi,

D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[60], T. Virdee[13], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, I. Macneill, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[61], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, J. Bendavid, A. Bornheim, J.M. Lawhorn, H.B. Newman, T. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki[62], W. Clarida, K. Dilsiz[63], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[64], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[65], Y. Onel, F. Ozok[66], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya,

D. Majumder, W. Mcbrayer, M. Murray, C. Royon, S. Sanders, E. Schmitz, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[34], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA
R. Ciesielski, K. Goulianos, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali[67], A. Castaneda Hernandez[67], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[68], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Suez University, Suez, Egypt
9: Now at British University in Egypt, Cairo, Egypt
10: Now at Helwan University, Cairo, Egypt
11: Also at Université de Haute Alsace, Mulhouse, France
12: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
13: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
14: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
15: Also at University of Hamburg, Hamburg, Germany
16: Also at Brandenburg University of Technology, Cottbus, Germany
17: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
20: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
21: Also at Institute of Physics, Bhubaneswar, India
22: Also at University of Visva-Bharati, Santiniketan, India
23: Also at University of Ruhuna, Matara, Sri Lanka
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Yazd University, Yazd, Iran
26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
27: Also at Università degli Studi di Siena, Siena, Italy
28: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
29: Also at Purdue University, West Lafayette, USA
30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
34: Also at Institute for Nuclear Research, Moscow, Russia
35: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at University of Florida, Gainesville, USA
38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Riga Technical University, Riga, Latvia
46: Also at Universität Zürich, Zurich, Switzerland
47: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
48: Also at Adiyaman University, Adiyaman, Turkey
49: Also at Istanbul Aydin University, Istanbul, Turkey
50: Also at Mersin University, Mersin, Turkey
51: Also at Cag University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Necmettin Erbakan University, Konya, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Istanbul Bilgi University, Istanbul, Turkey
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
60: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
61: Also at Utah Valley University, Orem, USA
62: Also at Beykent University, Istanbul, Turkey
63: Also at Bingol University, Bingol, Turkey
64: Also at Erzincan University, Erzincan, Turkey
65: Also at Sinop University, Sinop, Turkey
66: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea